



# Dark Matter Searches with the ANTARES Neutrino Telescope

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## Abstract

The ANTARES Collaboration is operating the largest water Cherenkov neutrino telescope in the Northern hemisphere, installed in the Mediterranean Sea. One of the objectives of ANTARES is the search for neutrinos produced in self-annihilation of Dark Matter particles. The results on the search for Dark Matter annihilations in the Sun and in the Galactic Centre with the data recorded between 2007 and 2012 are presented. The search on the Sun has resulted in competitive limits on the WIMP-proton cross-section, and they are compared to the ones of other indirect and direct detection experiments as well as to predictions of SUSY models. Results of ANTARES on Dark Matter searches towards the Galactic Centre have concluded with competitive limits on the annihilation cross-sections for high mass WIMPs that disfavours the interpretation of the PAMELA electron/positron excesses (constrained by Fermi-LAT and H.E.S.S.) as a signal from dark matter self-annihilations.

**Keywords:** Dark Matter; WIMP; neutrino telescopes;

## 1. Introduction

Observations in cosmology and astrophysics seem to indicate that about 84% of the matter in the Universe is non-baryonic, non-relativistic and does not interact electromagnetically but only significantly through the gravity, the so-called dark matter. A common assumption in the particle physics community is that dark matter is made of Weakly Interacting Massive Particles (WIMPs) that form a halo in which the visible baryonic part of galaxies is embedded. There are a variety of candidates for WIMPs, among which those provided by theories based on supersymmetry (SUSY) attract a great deal of interest. In some classes of minimal supersymmetric and universal extra-dimensional extensions of the Standard Model (MSSM and mUED), the lightest particle is stable. Consequently, these particles can only annihilate in pairs, making them a possible WIMP

candidate for dark matter. In these models, secondary high-energy neutrinos are produced from the self-annihilation products, or decays of them. The search for WIMPs can be performed either directly by recording the recoil energy of nuclei when WIMPs scatter on them in suitable detectors, or indirectly. The indirect approach, which is adopted here, exploits a radiation signature (gamma-ray, synchrotron, positron, anti-proton or neutrino flux) produced by the self-annihilation of WIMPs accumulated in heavy astrophysical objects such as the Galactic Centre (GC), the Sun or the Earth.

In this paper an indirect search for dark matter by looking for high-energy neutrinos coming from the Sun and the GC, using the 2007-2012 data recorded by the ANTARES neutrino telescope, is presented. One of the advantages of this kind of searches, especially for the case of the Sun, compared to other indirect searches such as for example looking for gammas from

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excess of positrons in the GC, is that a potential signal would be a very robust indication of dark matter, since other astrophysical explanations are much less plausible.

## 2. The ANTARES detector

The ANTARES neutrino telescope [1] is located in the Mediterranean Sea, at a depth of 2.5 km, about 40 km off Toulon (France). It consists of 885 Optical Modules (OMs) arranged in a three-dimensional array. The operation principle is based on the detection by these OMs of the Cherenkov light induced by relativistic muons produced in interactions of high energy neutrinos in the surroundings of the detector. The OMs are installed along 12 lines anchored to the sea floor and kept vertical by buoys at the top of them. The length of the lines is 450 m and the distance between the lines is 60–75 m. The OMs are grouped in triplets in order to reduce the effect of optical background produced by  $^{40}\text{K}$  and bioluminescence. The position [2] and time [3] information of the photons detected by the OMs can be used to reconstruct the muon direction. The detection events are classified as multi-line events if the photons hit several detection lines or singleline events if just one line is fired. For the latter, usually associated to lower energy muons, only the zenith direction can be determined and a zenith band is used to select the source. For multiline events all the direction information (zenith and azimuth) can be determined and a cone opening angle,  $\Psi$ , is used to analyse the source. Two reconstruction algorithms are used. The first one, BBFit, is based on the minimisation of a  $\chi^2$ -like quality parameter of the reconstruction,  $Q$ , which uses the difference between the expected and measured times of the detected photons taking into the effect of light absorption in the water [4]. The second one, AAFit, consists of a multi-step procedure to determine the direction of the reconstructed muon track from the time of arrival of photons by maximizing a maximum-likelihood ratio,  $\Lambda$ , which describes the quality of the reconstruction [5]. In addition to the  $\Lambda$  parameter, the uncertainty of the muon track direction angle,  $\beta$ , is estimated from the uncertainty on the zenith and azimuth angles drawn from the covariance matrix. These two algorithms present different efficiencies of reconstruction, denoted by the effective areas ( $\text{m}^2$ ) for muon neutrinos and antineutrinos of given energy (GeV), which represent the 100% efficient surface detecting neutrinos with a same event rate than ANTARES for a

given neutrino flux. Both are used since BBFit is more efficient for lower energies (or lower dark matter masses) and AAFit is more efficient at high energies (or high dark matter masses). The transition, roughly speaking, is around hundreds of GeV.

The installation of the detector was completed in 2008, although during 2007 five lines were already installed. In these dark matter searches data recorded between the 27th of January 2007 and the 31st of October 2012 are used, corresponding to a total lifetime of 1321 days, without taking into account the visibility of the Sun or GC. During this time, the detector consisted of 5 lines for most of 2007 and of successively 8, 9, 10 and 12 lines from 2008 to 2012.

## 3. Signal and background estimation

The signal, i.e. the flux of muon neutrinos as a function of their energy arriving at the Earth's surface from the source is computed using Monte Carlo packages and results (WimpSim [6] for the Sun and [7] for GC). With this, neutrinos for the relevant channels and for dark matter masses ranging from 25 GeV to 10 TeV are derived. Propagation effects, i.e. oscillations among the three neutrino flavours, neutrino absorption and regeneration, are taken into account by these Monte Carlo packages.

There are two sources of background in the ANTARES detector: the muons and neutrinos produced by cosmic rays interacting in the atmosphere. In order to reduce the first one, only upgoing events are selected, since muons cannot traverse the Earth. However, some of these muons (a tiny fraction of the total, but non-negligible number given the flux involved) are misreconstructed as upgoing. This is why further cuts are needed on the quality of the reconstructed track in order to reject them. On the other hand, the atmospheric neutrinos are irreducible background. The background estimation is done by scrambling real data using random times, which reduces the impact of systematic uncertainties.

## 4. Optimization

A blind strategy procedure has been followed for the analysis in order to avoid selection biases. This means that the cuts have been selected before looking at the source region. The criterion to choose the cuts has been to optimize (minimize) the average upper limit which can be set for any given dark matter mass and channel. This has been done using Feldman-Cousins method [8] and using an average effective

area that takes into account the lifetime of each detector configuration [9].

The optimization is done by scanning the average upper limit for different values of cuts in the search cone angle around the Sun direction,  $\Psi$  (zenith band for single line events) and the quality parameter assigned by the reconstruction algorithm,  $Q$  or  $\Lambda$  and  $\beta$ . For each WIMP mass and channel, an optimized set of cuts is found using the blind procedure.

## 5. Results

Once the selection cuts have been optimized, the signal region is looked at. In the next sections, the results for the Sun and GC dark matter searches are presented.

### 5.1. Results of the dark matter search in the Sun

As shown in Fig. 1, no excess over the background has been found, so upper limits in the neutrino flux can be set. By assuming equilibrium between capture and annihilation rate of dark matter in the Sun, which is usually assumed, this can be translated into limits on the spin dependent (and spin independent) cross-section of the WIMP-proton scattering for the case in which one of them is dominant. This is presented in Fig. 2 compared to different experimental limits and with the parameter space derived from the CMSSM and MSSM-7 models.

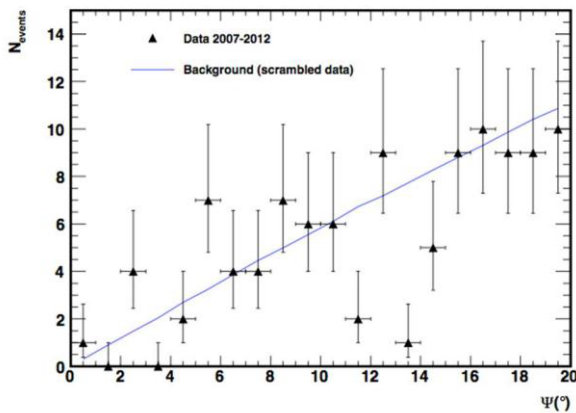


Fig. 1. Differential distribution of the angular separation  $\Psi$  of the event tracks with respect to the Sun's direction compared to the expected background (solid blue line) for multiline events with BBFit reconstruction  $Q < 1.4$ , which is used for a large fraction of dark matter searches in the Sun (channels and masses).

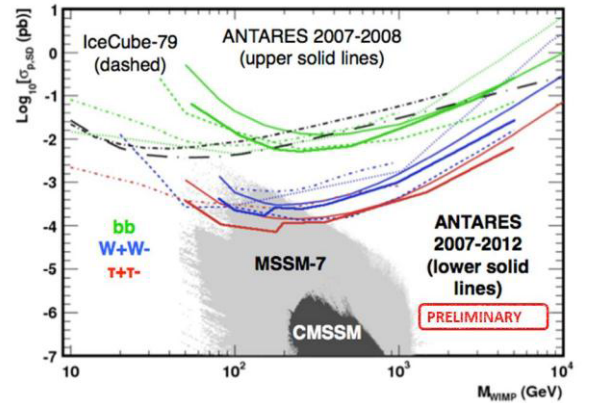


Fig. 2. 90% CL upper limits on the SD WIMP-proton cross-sections as a function of the WIMP mass, for the three self-annihilation channels:  $bb_{\text{bar}}$  (green),  $W+W-$  (blue) and  $\tau+\tau-$  (red), for ANTARES 2007–2008 [9] (upper solid lines) and ANTARES 2007–2012 (lower solid lines) compared to the results of other indirect search experiments: Baksan 1978–2009 [10] (dash-dotted lines), Super-Kamiokande 1996–2008 [11] (dotted lines) and IceCube-79 2010–2011 [12] (dashed lines) and the results of direct search experiments (black): SIMPLE2004–2011 [13] (short dot-dashed line), COUPP2010–2011 [14] (long dot-dashed line). The results of a grid scan of the CMSSM and CMSSM-7 are included (grey shaded area) for comparison.

### 5.2. Results of the dark matter search in the Galactic Center

No significant excess over the background has been found in the dark matter search in the GC, as shown in Figs. 3 and 4.

Since there is no excess, upper limits for the neutrino fluxes from the GC for the different dark matter masses and channels can be set. These limits can be translated into limits on mean cross-section velocity product for dark matter,  $\langle \sigma_A v \rangle$ , by considering a galactic halo model. Fig. 5 shows these limits considering the usual NFW [15] profile for the Milky Way. Different channels are shown in this plot, and the three cases of reconstruction algorithm and kind of events used are compared.

Finally, the upper limits on the WIMPs velocity averaged self-annihilation cross-section,  $\langle \sigma_A v \rangle$ , as a function of the WIMP mass for the self-annihilation channels WIMP-WIMP into  $\tau+\tau-$  for ANTARES 2007–2012 with AAFit and BBFit results combined is presented in Fig. 6. The results are compared with Icecube and Fermi results on this and with the regions favoured by PAMELA, Fermi-LAT and H.E.S.S. interpreted as dark matter self-annihilations. The band indicating the natural scale for which all the dark

Figure 1 is a plot showing the number of events ( $N_{\text{event}}$ ) as a function of the angle  $\Psi$  (in degrees). The y-axis ranges from 0 to 70, and the x-axis ranges from 0 to 45. The data points are represented by black stars with vertical error bars. A solid blue line represents the fit to the data. The number of events starts at approximately 55 at  $\Psi = 0^\circ$  and decreases to about 25 at  $\Psi = 45^\circ$ .

Figure 1 is a plot showing the number of events ( $N_{\text{events}}$ ) versus the angle  $\Psi$  (in degrees). The data points are represented by black crosses with vertical error bars, and a solid blue line represents the fit. The x-axis ranges from 0 to 45 degrees, and the y-axis ranges from 0 to 70 events. The data shows a general upward trend with some fluctuations.

The ANTARES data corresponding to 2007–2012 have been used to search for an excess of high energy neutrinos in the Sun's and GC's direction, which could indicate annihilation of dark matter particles. The

binned search analyses have shown no excess with respect to the expectations from background. Upper limits in the neutrino fluxes have been set.

From the results in the Sun and assuming that equilibrium between capture and annihilation has been reached, these flux limits can be translated into limits in the spin dependent and spin independent cross-section of the WIMP-proton scattering in a range of WIMP masses of [25GeV - 10TeV]. The results for spin dependent cross-section are particularly competitive with respect to direct search experiments. A comparison with the parameter space allowed by the CMSSM and MSSM-7 models has also been shown.

From the results in the GC, upper limits on the WIMPs velocity averaged self-annihilation cross-section,  $\langle\sigma_{AV}\rangle$ , as a function of the WIMP mass for different self-annihilation channels have been derived in a range of WIMP masses of [25GeV - 10TeV]. The 90% C.L. upper limit in  $\langle\sigma_{AV}\rangle$ , stated for the channel WIMP-WIMP into  $\tau^+\tau^-$  appears to be the most stringent as coming from a neutrino telescope, when it is consistent with the most constraining upper limits performed thanks to the Fermi-LAT and MAGIC [20] observatories. Furthermore, the performance of the ANTARES neutrino telescope through this study allows to reject at 90% C.L. an interpretation of the PAMELA electron/positron excesses (constrained by Fermi-LAT and H.E.S.S.) as a signal from dark matter self-annihilations.

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